Integrated, Flexible, High-efficiency Solar Cells:

Epitaxial Lift-Off GaAs Solar Cells and Enabling Substrate Reuse

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OPTOELECTRONIC COMPONENTS & MATERIALS

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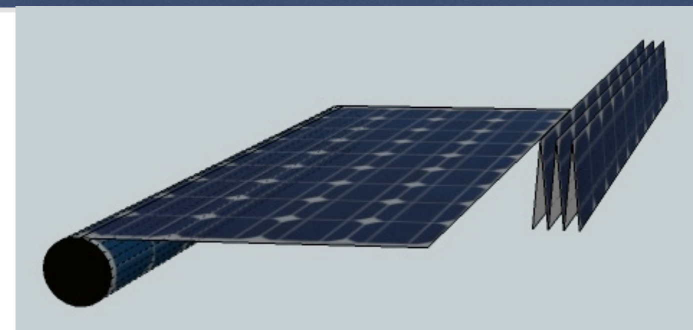
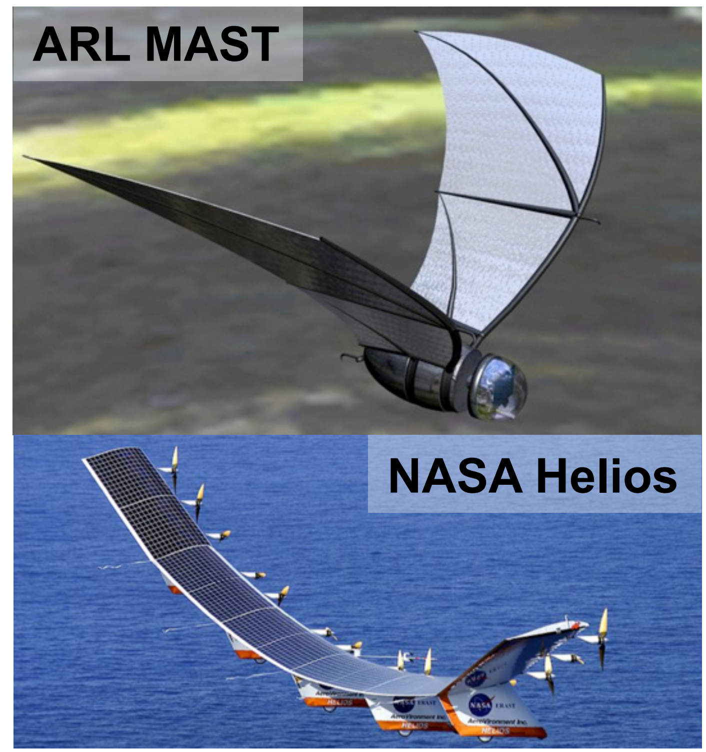
Motivation

- Numerous uses for **lightweight, high-efficiency, flexible** photovoltaics:
  - Power at temporary off-grid locations.
  - Autonomous vehicles (e.g. UAVs).
  - Satellites.
- No available technologies provide high-efficiency, high power density photovoltaics on lightweight flexible substrates.
- III-V photovoltaics provide >28% power conversion efficiency (η_P).
- Specific power densities of >6 W/g & 280 W/m^2.
- Substantial reduction in III-V PV cost structure: wafer reuse.

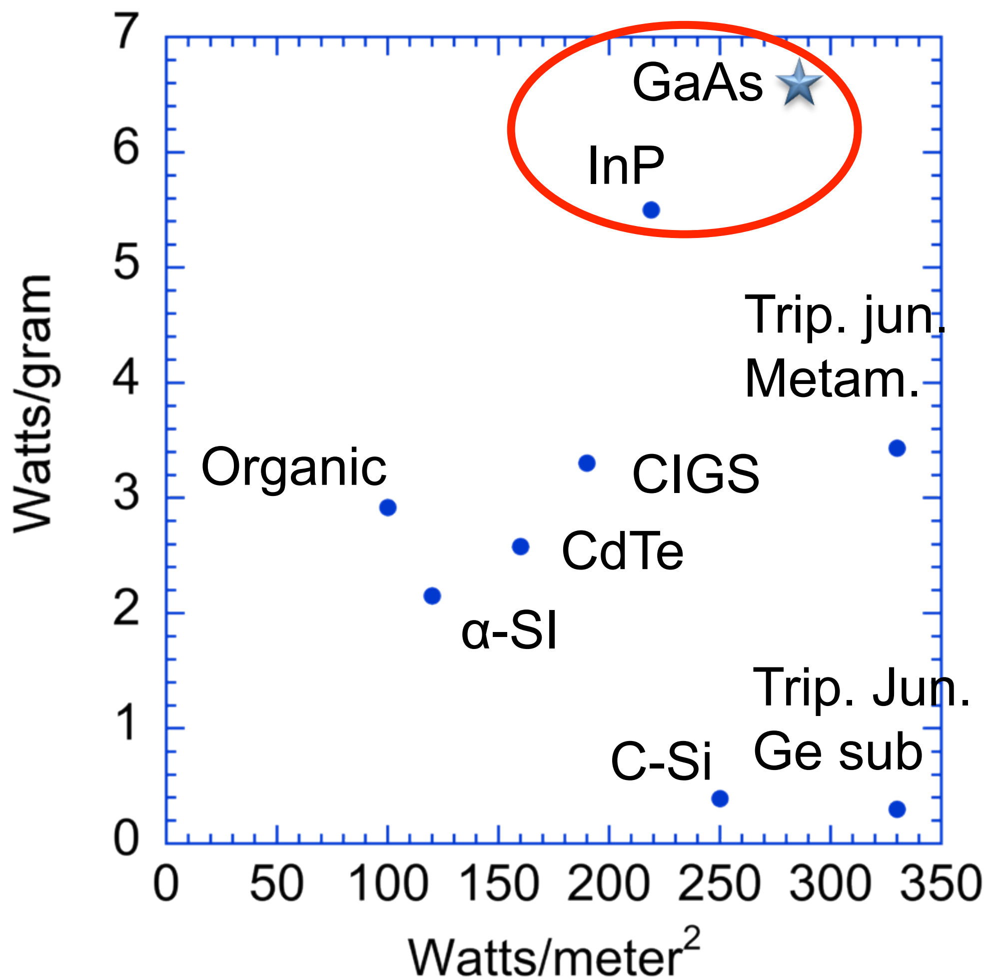


Rollable or foldable portable PV



Power for UAVs

Power/Weight Tradeoff



- Ideal cell:
  thin + high efficiency.
- Active layers for GaAs cell is ~2 µm.
- Lift-off uses back reflector → active layer thickness reduced by ~50%.
- GaAs has highest power:area and power:weight ratios achievable.
- Lift-off cells have higher power conversion efficiency than substrate cells.

Technologies & Goals

Epitaxial Lift-Off (ELO)

- **Light Weight & Flexible Thin-Film Solar Cell**

  E. Yablonovitch et al, Appl. Phys. Lett. **51**, 2222 (1987).

Epitaxial Protection Layers

- **Parent Wafer Reuse**

  K. Lee et al, Appl. Phys. Lett. **97**, 101107 (2010)—**UM.**

Cold Welding

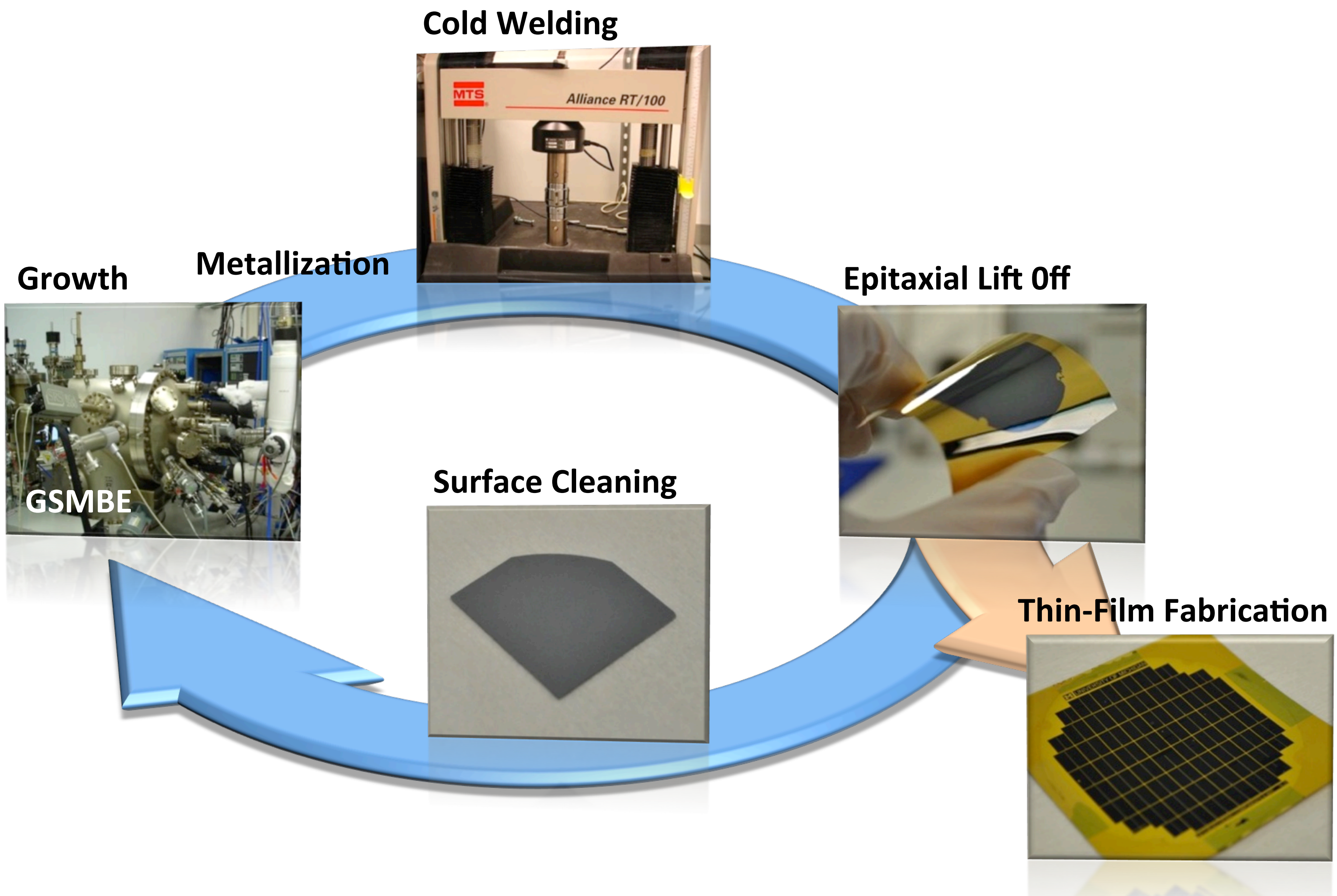
- **Simplified Transfer Process**

  K. T. Shiu et al, Appl. Phys. Lett. **95**, 223503 (2009)—**UM.**

Multiple Growths on Single Wafer

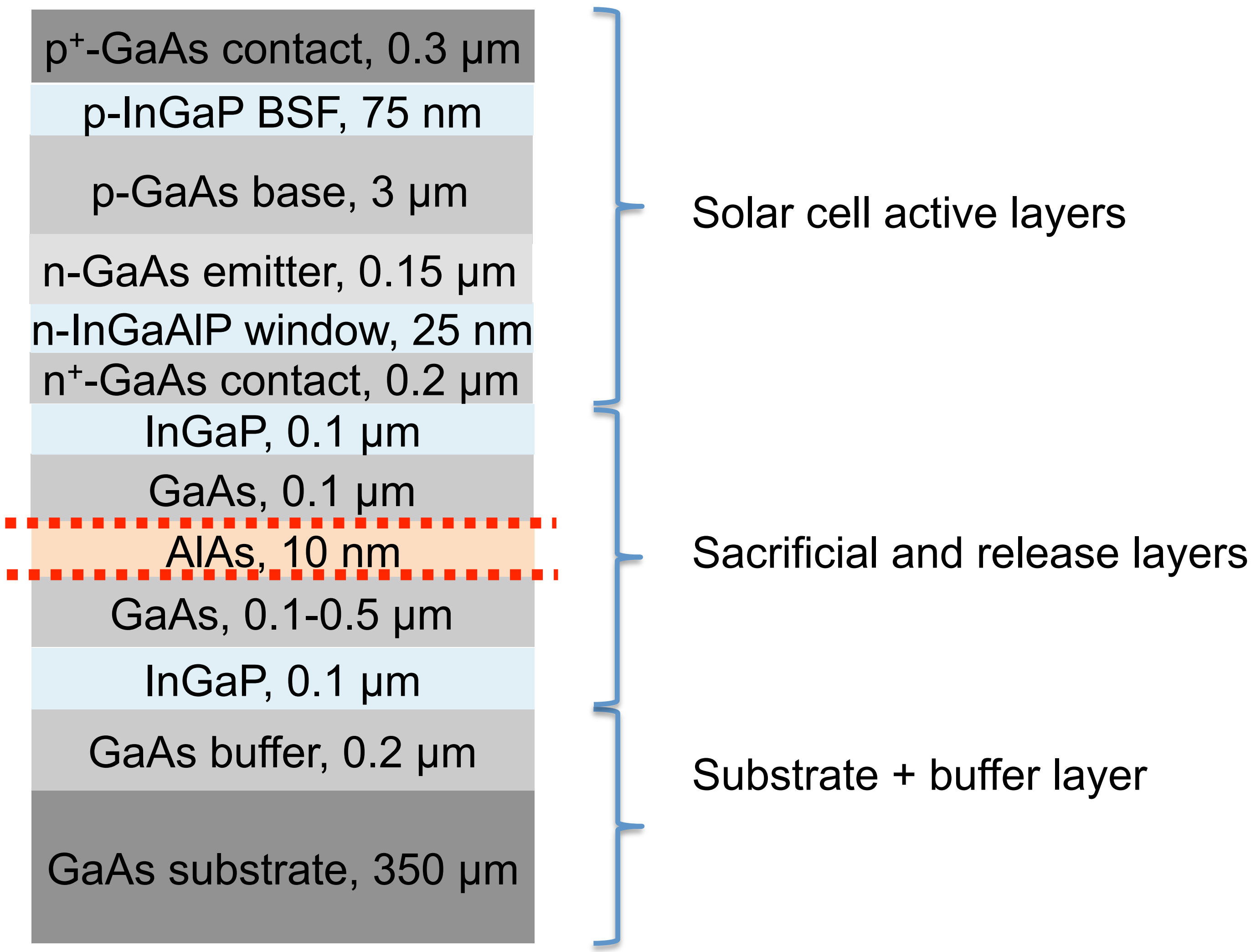
Low-Cost Solar-to-Electrical Energy Conversion

Non-Destructive Wafer Reuse for Thin-Film PV Cells



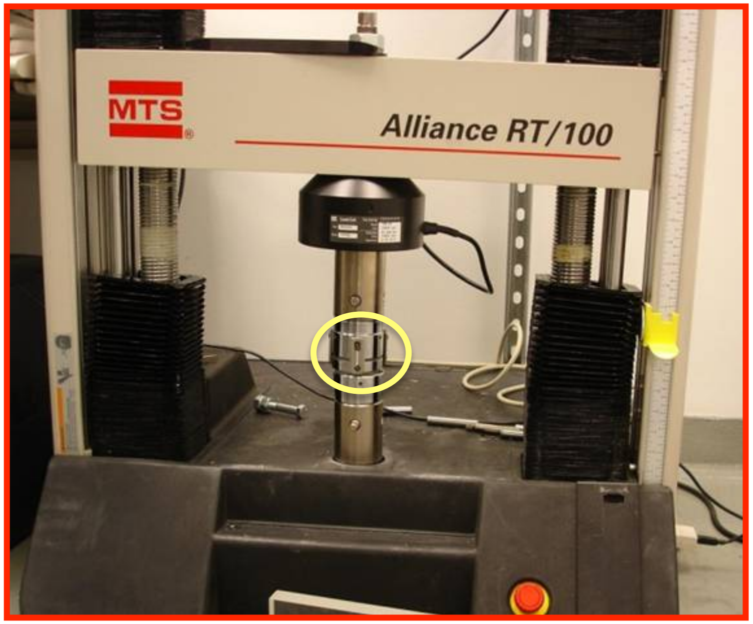
MBE Growth of Epi-layers

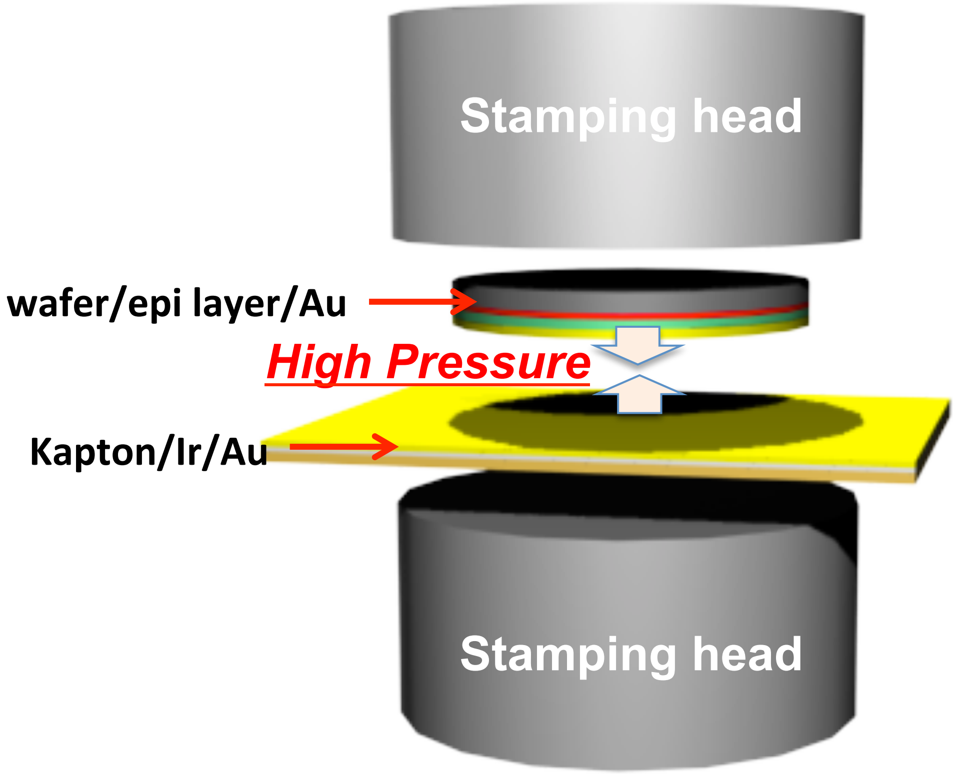
Molecular beam epitaxy used to grow:



Cold Welding

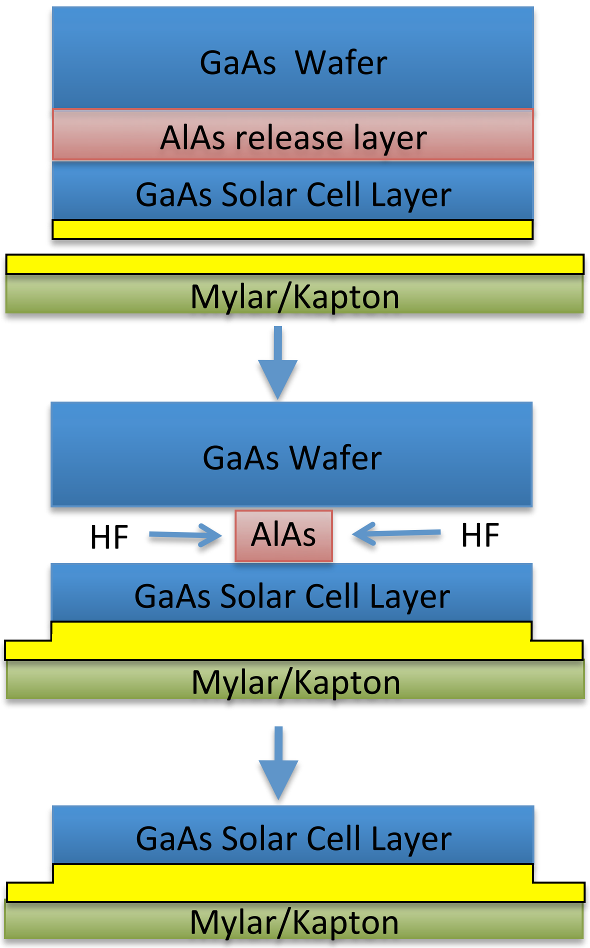
- Au deposited on wafer and plastic handle.
- Au surfaces bonded by applying pressure.
  - Metallic bonds formed at room temperature.
  - Adhesive-free bonding technology.
- Simple transfer process.

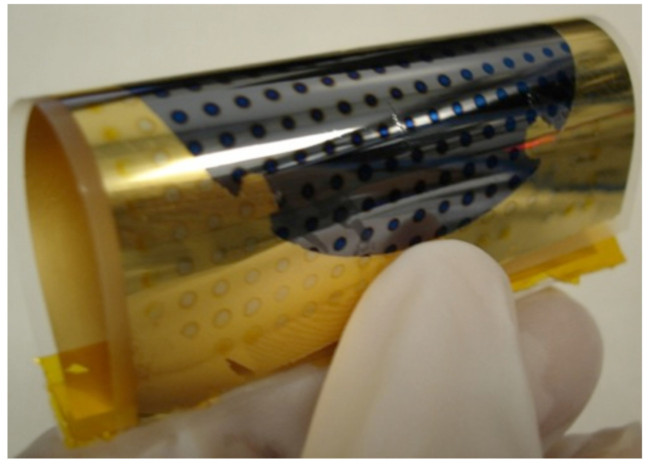


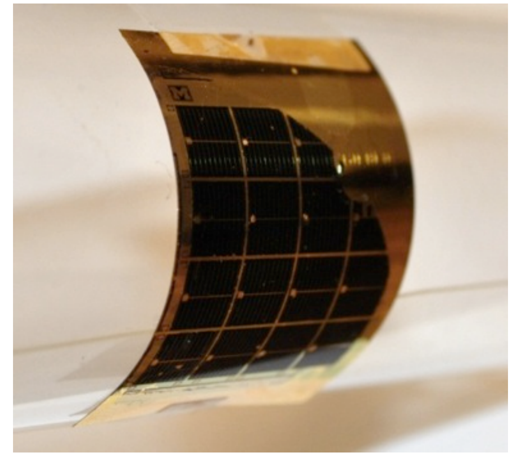


Transferring III-V PV Cells to Plastic

Epitaxial lift-off



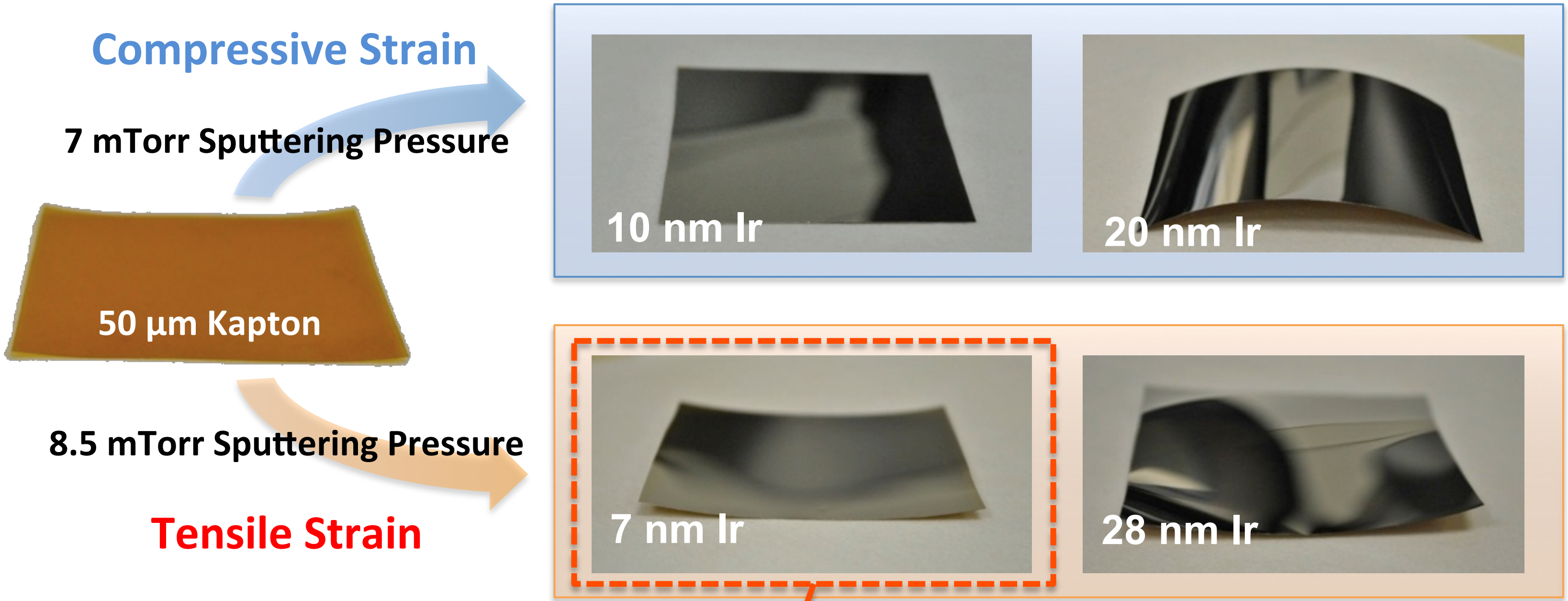


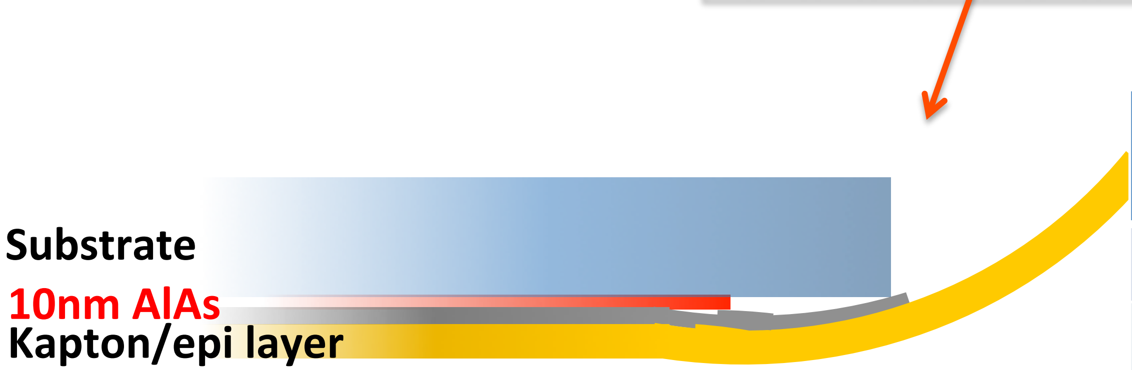


- Wafer cold welded to Kapton®.
- Lift off performed with HF.
  - Etch selectivity is ~10^7:1 (AlAs:GaAs).
  - Epitaxial lift-off enables wafer reuse.
  - Efforts are focused on improving quality and speed of lift-off process.
- Fabrication performed on Kapton® substrate.
- Flexible without degradation to radius < 1 cm.

Acceleration of ELO Using Strained Handles

Strain Control by Sputtered Ir

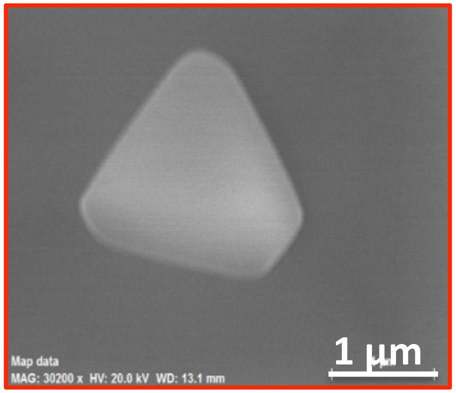




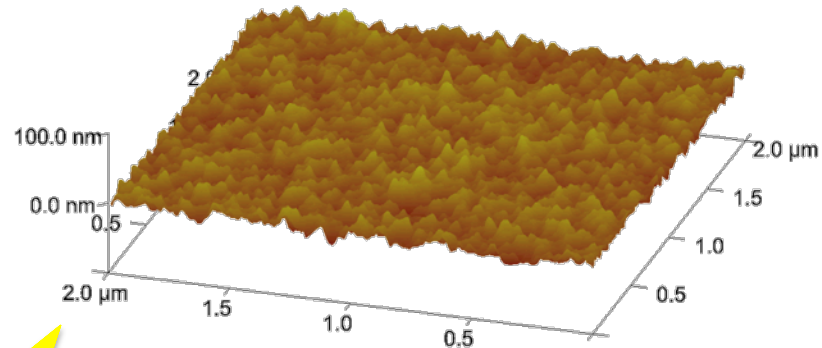
Strain State (Ir thickness)	Etch time
Neutral	~10 days
Compressive (21 nm)	~24 hrs
Tensile (7 nm)	<8 hrs

Influence of ELO on GaAs Wafer

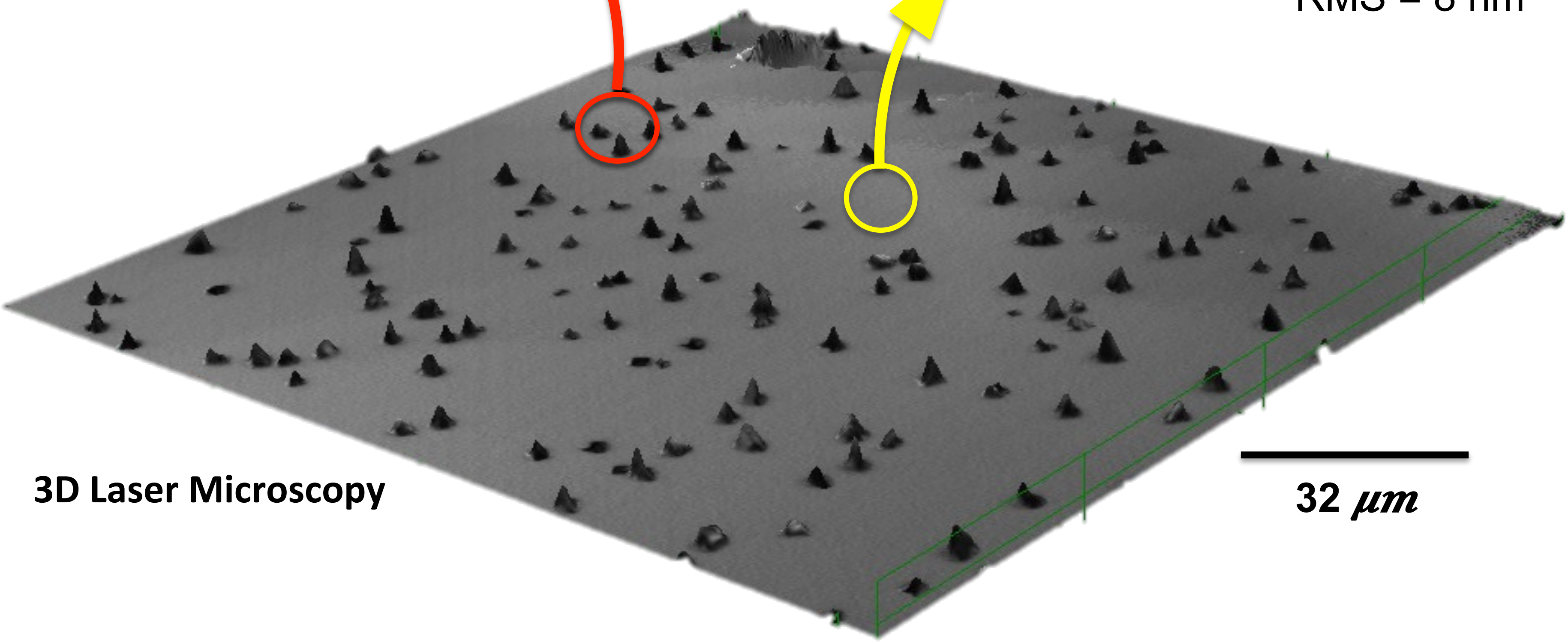
Scanning Electron Microscopy



Atomic Force Microscopy



RMS = 8 nm

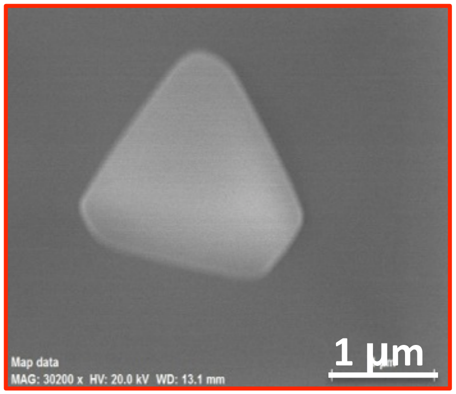


3D Laser Microscopy

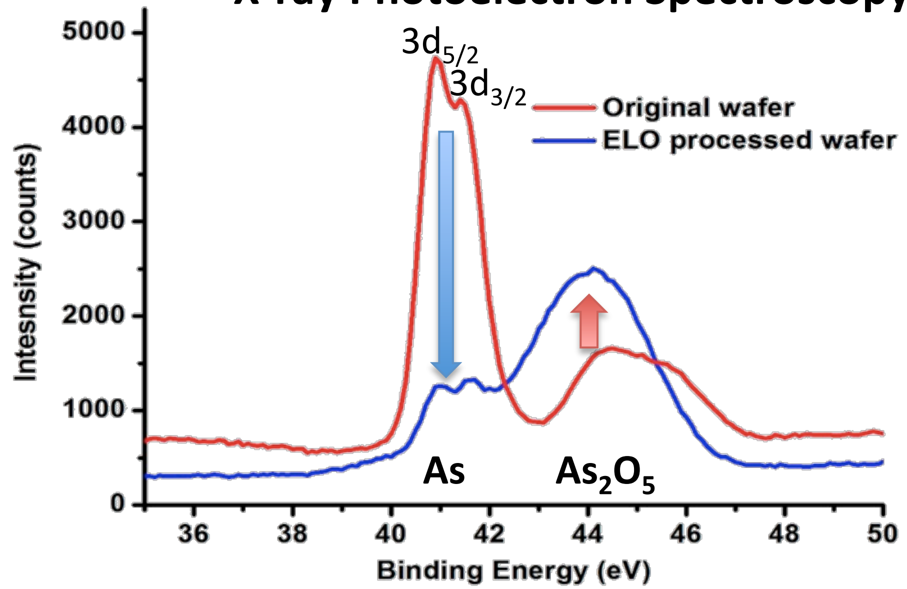
32 μm

Influence of ELO on GaAs Wafer

Scanning Electron Microscopy

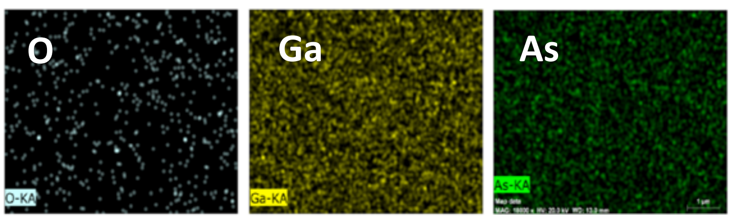


X-ray Photoelectron Spectroscopy

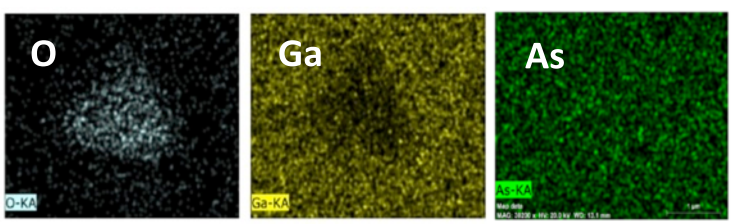


Energy Dispersive Spectroscopy

Original Wafer

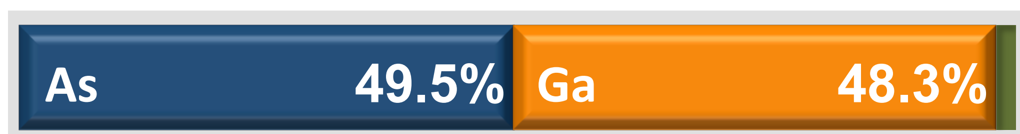


ELO Processed Wafer



Atomic Concentration Near Surface

Original Wafer



ELO Processed Wafer

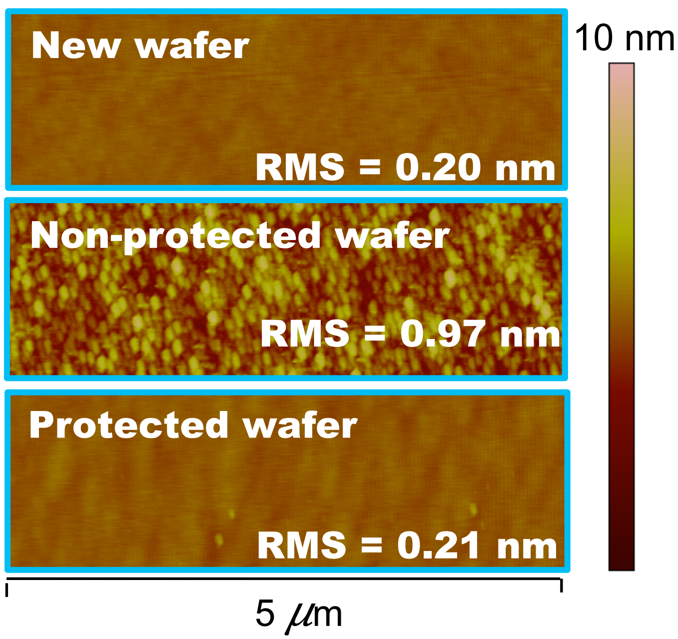
Protection Layers

Protection Layer Structure

⋮

$In_{0.49}Ga_{0.51}P$ (0.1 μm)
AlAs (10 nm)
$In_{0.49}Ga_{0.51}P$ (0.1 μm)
GaAs (0.1 μm)
$In_{0.49}Ga_{0.51}P$ (0.1 μm)
GaAs wafer

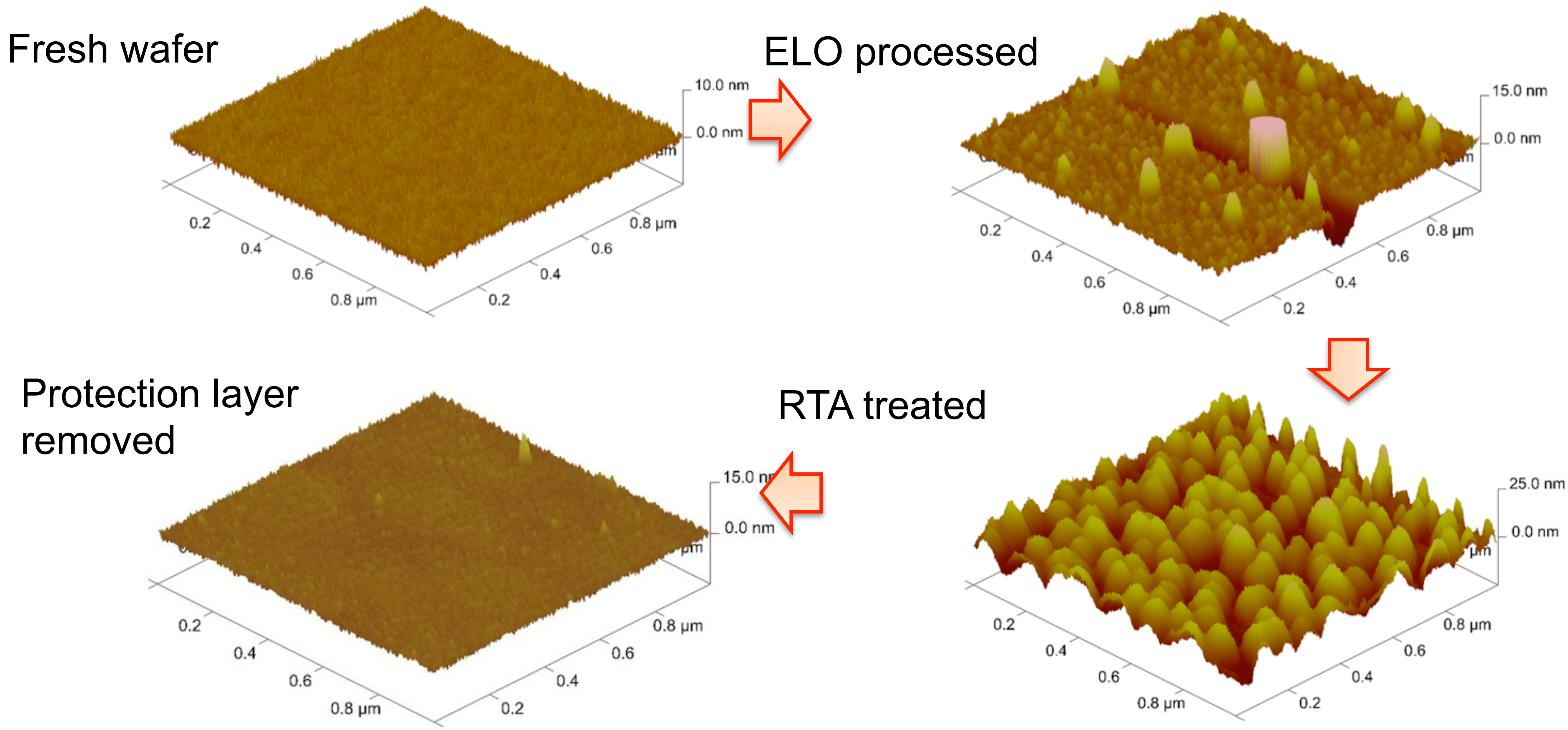
Atomic Force Microscopy



- Protection layers
  - Inserted between AlAs and wafer or active layers.
  - Prevent HF from contacting the wafer.
  - InGaP removed with H_3PO_4:HCl or HCl:H_2O.
  - GaAs removed with H_3PO_4:H_2O_2: H_2O.
  - Reduces RMS roughness to that of original wafer.
- As_2O_5 particles difficult to remove
  - Tri-layer necessary.
  - Over-etched to undercut particulates.

K. Lee et al, APL **97**, 101107 (2010).
K. Lee et al, JAP **111**, 033527 (2012).

Thermal Decomposition

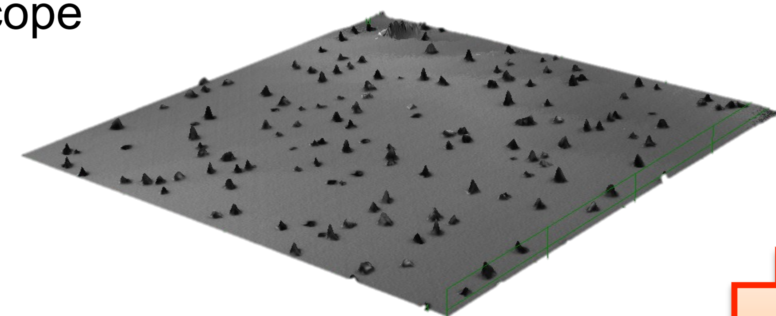


- RTA in N_2 at 600 °C for 1 min.
- GaAs/InGaP bilayer protection removed with wet etches.
- Surface returned to like-new condition.

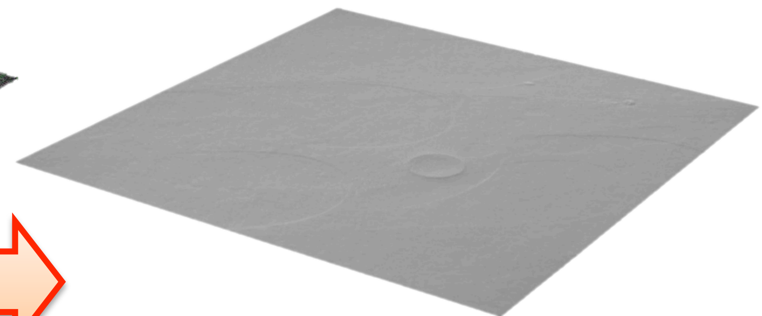
Plasma Pre-clean

3d laser microscope

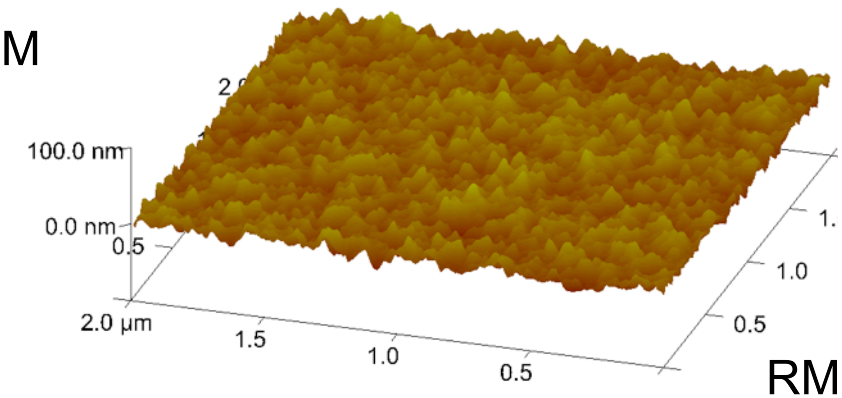
After ELO



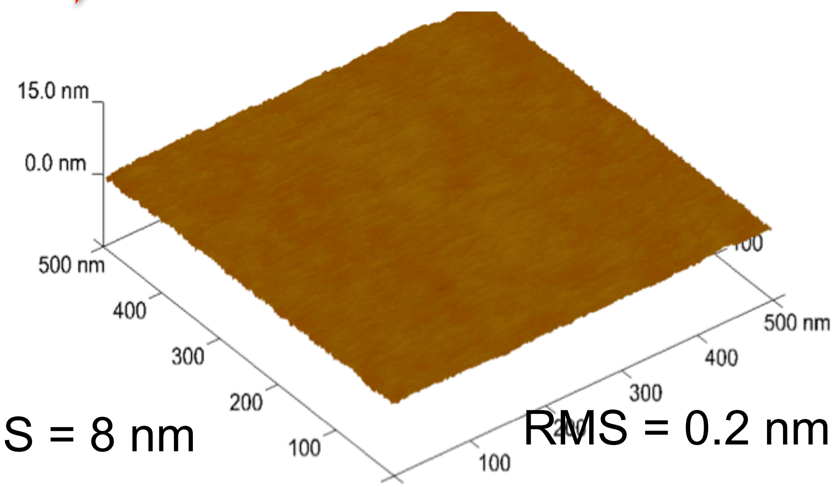
After plasma cleaning



AFM



RMS = 8 nm

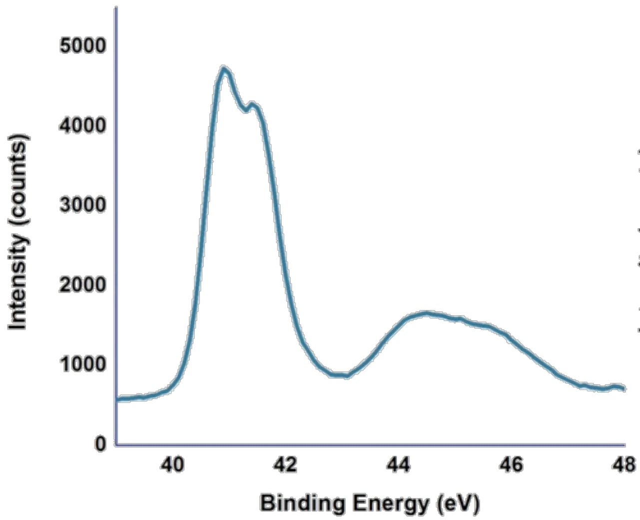


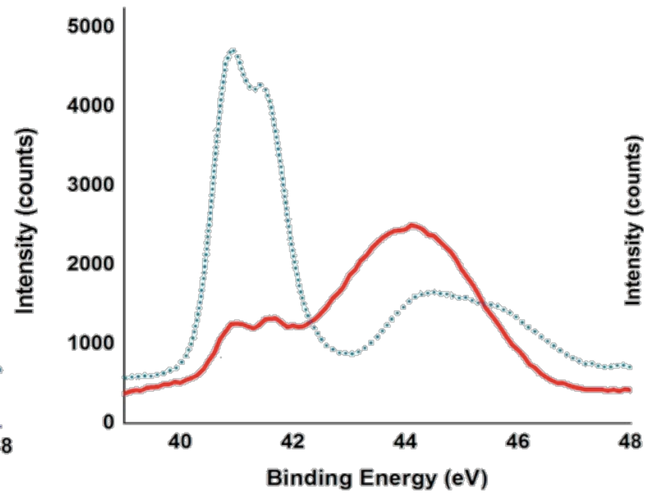
RMS = 0.2 nm

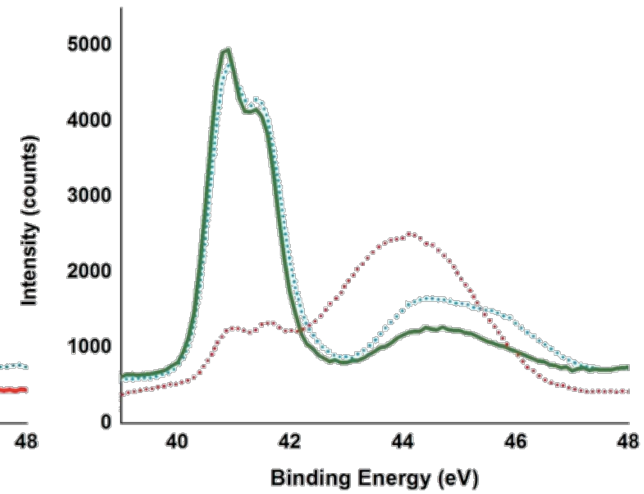
- SF_6+Ar ICP plasma for 1 min.
- GaAs/InGaP bilayer protection removed with wet etches.
- Surface returned to like-new condition.

Surface Chemistry Comparison

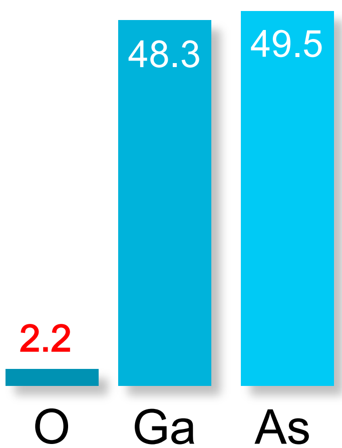
X-ray Photoelectron Spectroscopy



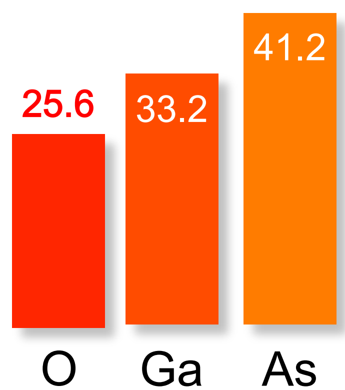




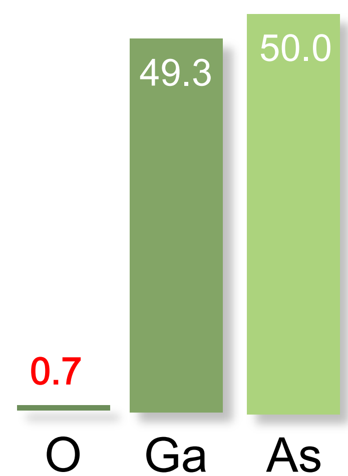
Energy Dispersive Spectroscopy



Original Wafer



ELO Processed Wafer



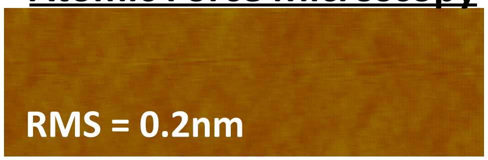
Surface Cleaned Wafer
After ELO

Epitaxial Protection Layer & Surface Cleaning

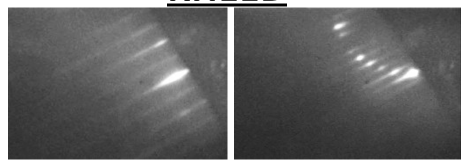
Substrate

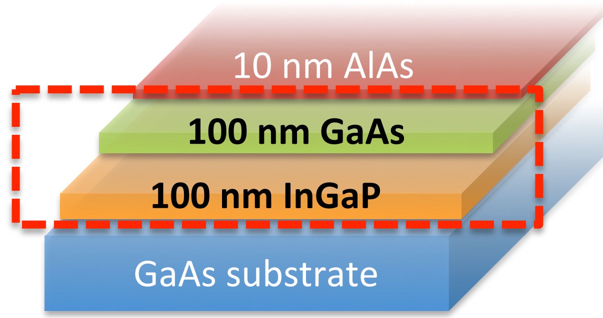
Original wafer

Atomic Force Microscopy



RHEED

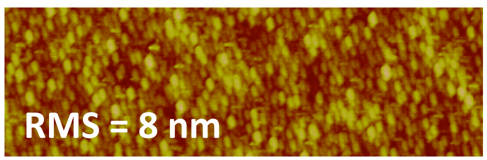


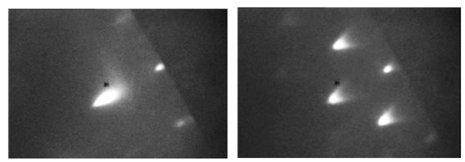


Growth

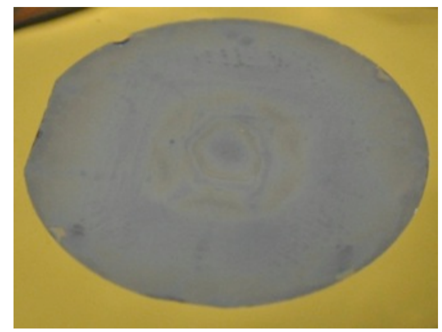
Metallization & Cold Welding

Epitaxial lift off





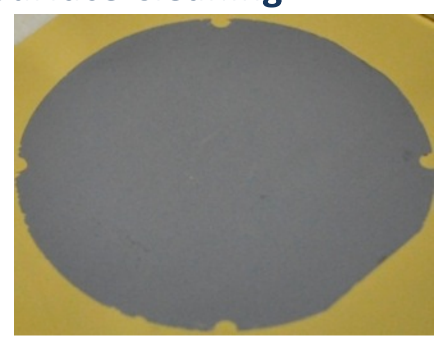
Thin-Film



Surface Pre-cleaning

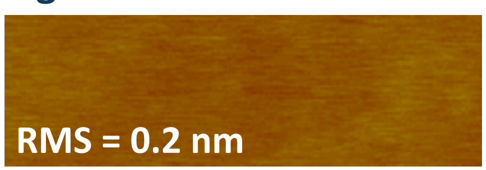
Thermal or Plasma Cleaning

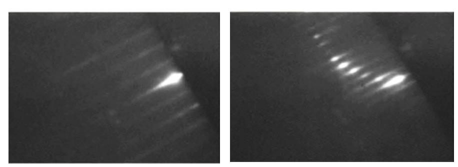
Surface Cleaning



Protection layer removal

Regrowth

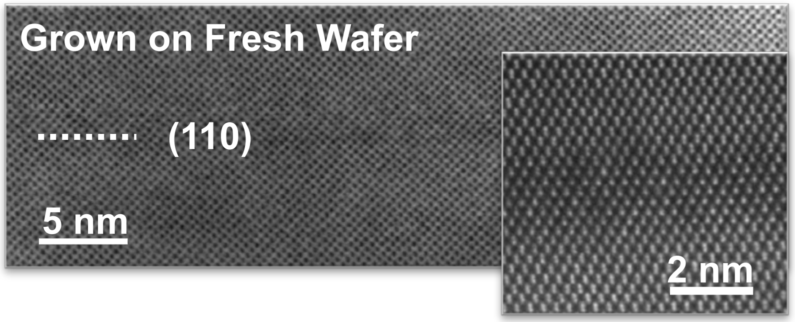


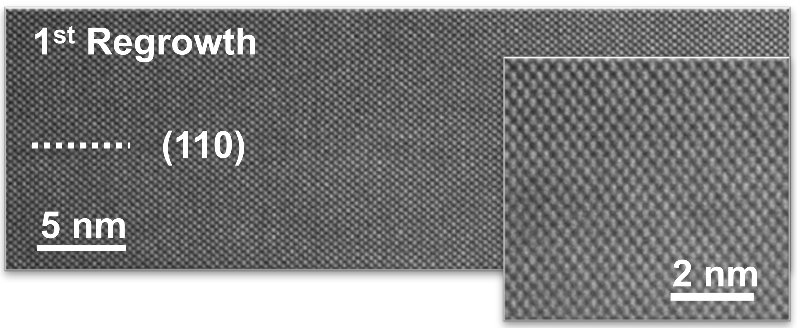


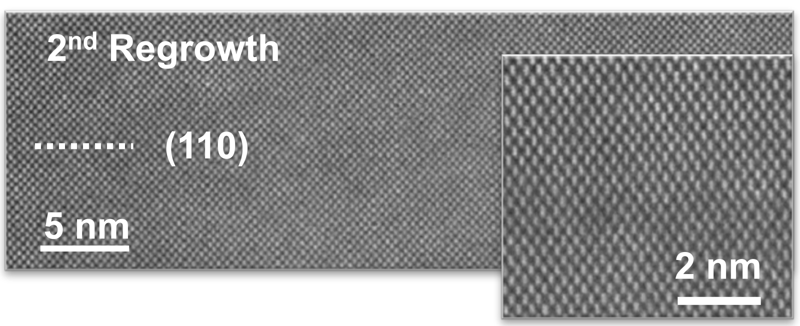
Solar Cell Fabrication

Growth Quality Comparison

Cross-Sectional Transmission Electron Microscopy







Hall Effect Measurement

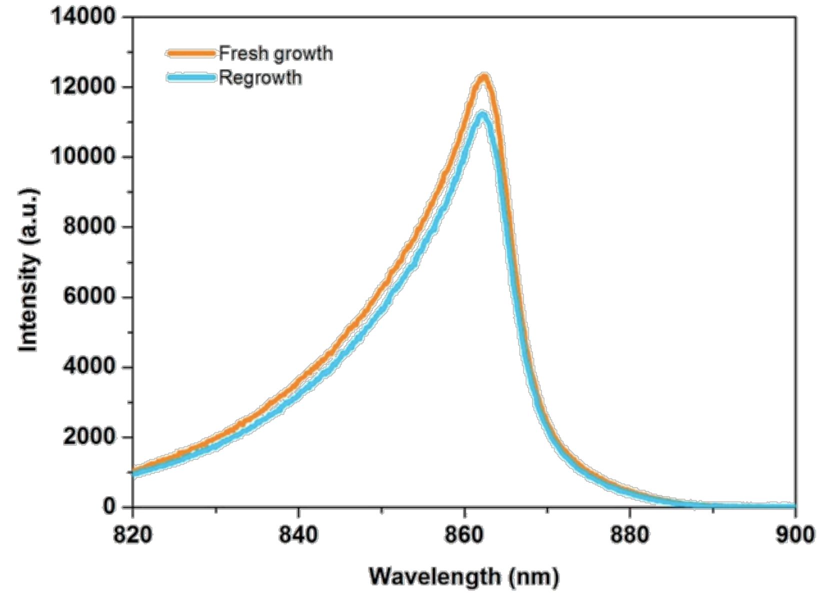
Original Growth

Doping concentration 1.67×10^{18} /cm^3 — 1950 cm^2/Vs

Regrowth

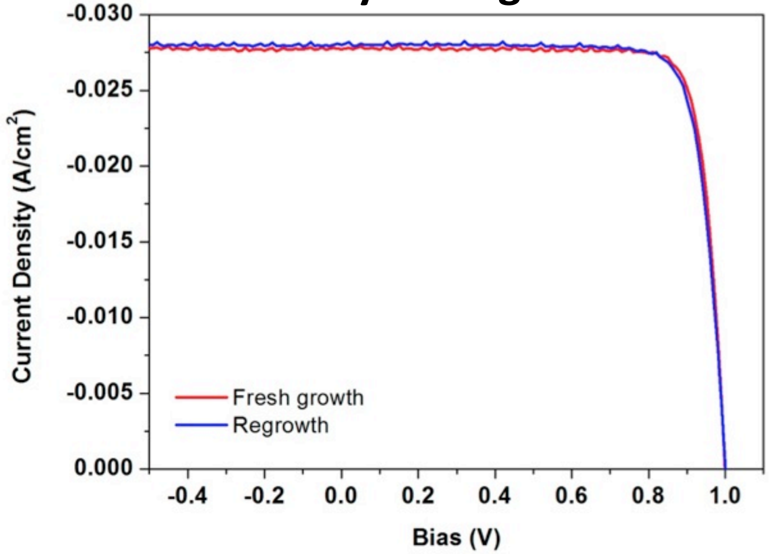
Doping concentration 1.78×10^{18} /cm^3 — 1930 cm^2/Vs

Photoluminescence Measurement

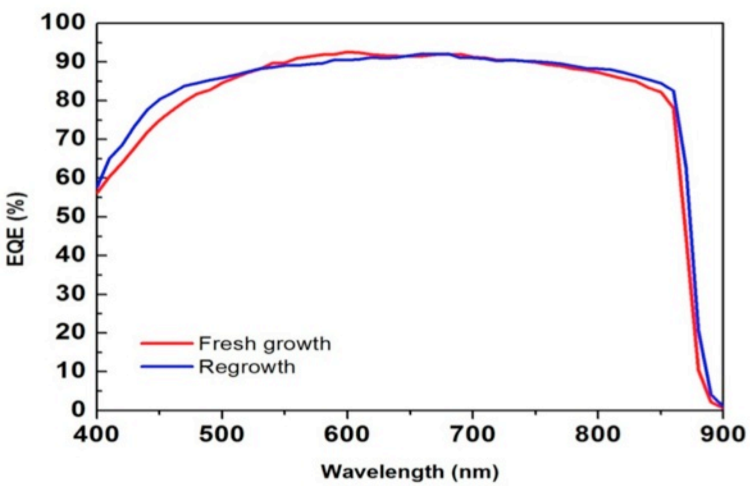


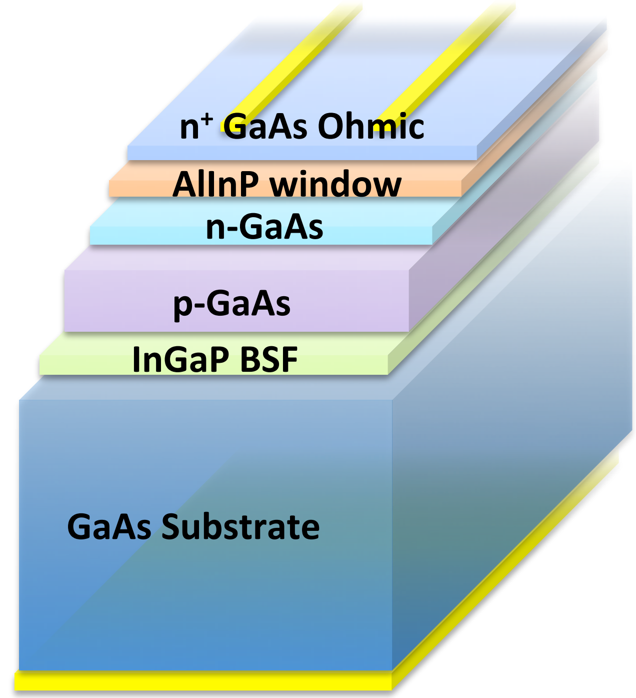
Device Performance Comparison

Current Density-Voltage Curve



External Quantum Efficiency



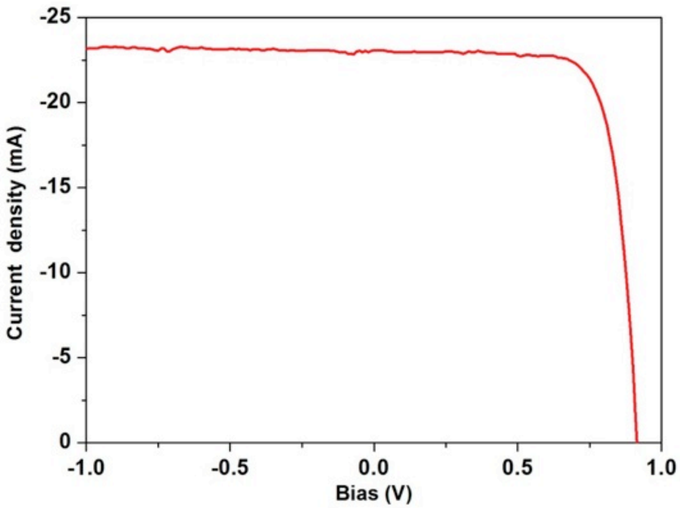


Device Efficiency Parameters

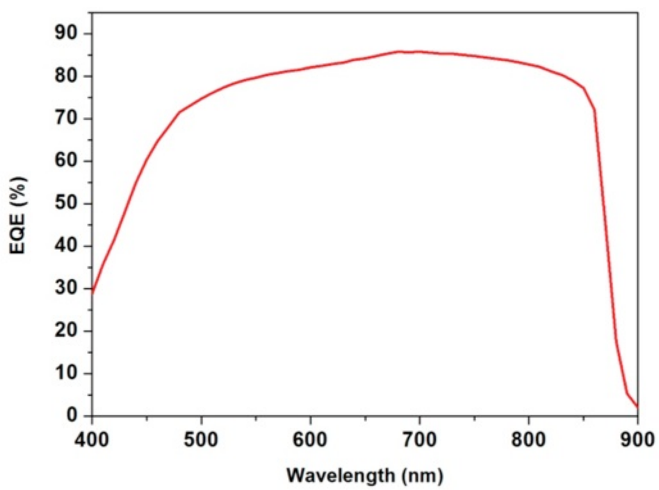
	J_{SC} [mA cm^{-2}]	V_{OC} [V]	FF [%]	PCE [%]
Fresh Wafer	27.7±0.5	1.00	83.4	23.1±0.6
Reused wafer	28.0±0.4	1.00	81.6	22.8±0.5

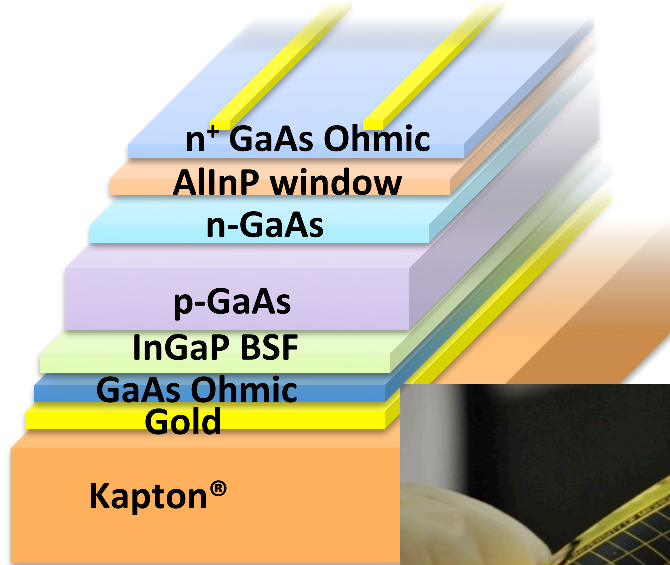
GaAs Thin-Film Solar Cells

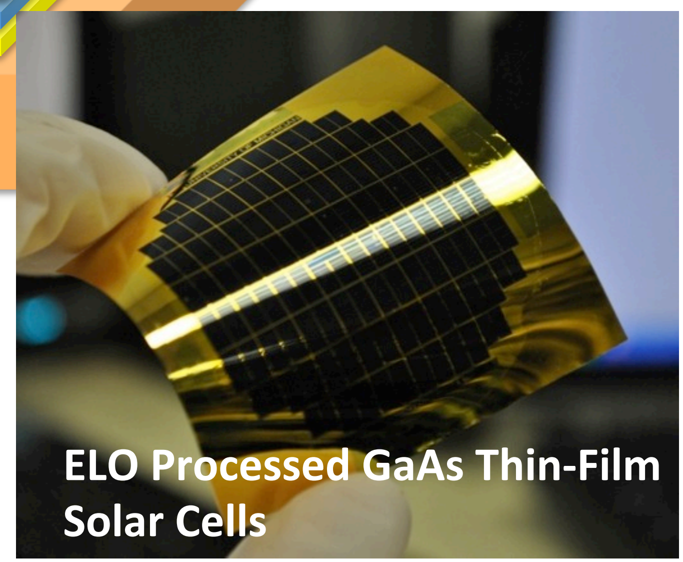
Current Density-Voltage Curve



External Quantum Efficiency







Device Efficiency Parameters

J_{SC}	V_{OC}	FF	PCE
23.1 mA/cm^2	0.92 V	75.6%	16.1%

Cost Estimate: Substrate-Based III-V PV

1 m^2 GaAs PV Cells:

- Substrates (56 x 6”) — $17,000
- Source material (4 µm GaAs growth) — $80
- Liquid nitrogen for cryo panels — $400
- Electricity (~120 kW-hr) — $15
- Wafer processing — $75
  - Conventional Au contacts — $40
  - AR coating (ZnS/MgF_2)150nm — $10
  - Lithographic patterning — $25
- Total — $17,570
- **Cost/Wp @ 23%** — **$76**

(assumptions: Standard **MBE** design, no large reductions in price for bulk quantities, and labor and capitol cost not included.)

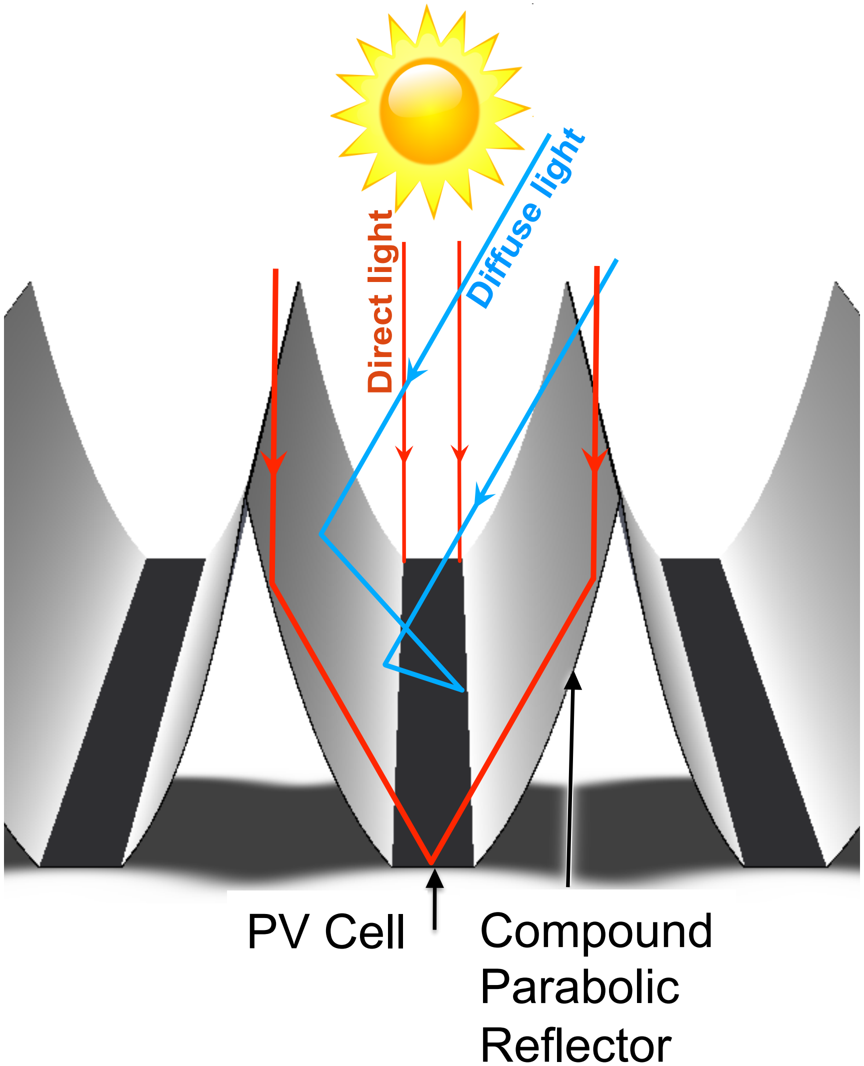
Cost Estimate for *Flexible* III-V PV

1 m^2 GaAs PV Cells:

• Substrates (56 x 6"): **50 uses**		**$340**
• Source material (**2 μm** GaAs growth)		**$40**
• Electricity (~120 kW-hr)		$15
• Wafer processing		$35
– Metal/Kapton® foil	$10	
– Ag/Cu contacts	$10	
– AR coating (ZnS/MgF_2)150nm	$5	
– HF etchant (HF:AlAs >106:1), 1 L 10%	$5	
– Non-Lithographic patterning	$5	
• Total		$430
• **Cost/Wp @ 30%**		**$1.43**

(assumption: **No LN_2**—requires MBE redesign.)

Concentration



- Grid parity possible by using concentrators.
- 4x concentration: ~$0.70/Wp.
- 10x concentration: ~$0.45/Wp.
- Requires solar tracking.

Summary

- **Solar Cell Fabrication**
  - Via cold-welding & epitaxial lift-off.
  - Expedited lift-off process using strained handle.
- **Reuse of GaAs Wafers**
  - Lattice matched epitaxial protection layer.
  - Thermal & plasma surface cleaning.
  - GaAs regrowth after protection layer removal.
  - Identical solar cell performance.

K. Lee et al, J. Appl. Phys. **111**, 033527 (2012).

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